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Dynamic Performance of High Bypass Ratio Turbine Engines With Water Ingestion

S.N.B. Murthy

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Acknowledgment

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1. Introduction

Adverse weather operation of turbojet and turbofan engines can lead to the ingestion of water in many forms into the engine: vapor, liquid, hail, slush, ice crystals, ice particles, and large ice pieces broken away from deposits on material surfaces in the vicinity of the engine. In all cases, the engine may suffer vibration, power loss, difficulty in regaining the lost power loss, stalling and surging of fan and compressors, difficulty in regaining normal operation in post-stall conditions, and, in the most severe cases, engine flameout, and difficulty in reignition procedures. The nature and extent of such effects depends on the engine design and its integration with the aircraft, flight and engine operating conditions, the form, characteristics, and amount of water ingested, and the response of the control system and the pilot.

Ingestion of water in various forms may occur during flight, take-off from runways, and icing of engine inlet or neighboring surfaces and subsequent break away of ice. It can also arise during engine testing due to condensation in the inlet under high humidity and moderate temperature conditions.

The problem of establishing changes in the operability and performance of a flight engine is of interest from several points of view: comfort and safety of flight operations; testing of the engine on ground during engine acceptance, and during development; and design of engine-aircraft integration, aircraft undercarriage and landing wheels, and the control system.

Other than mechanical effects due to the impact of particulates, the main aerothermal effects are due to the flow changes occurring on account of the two and three phase nature of the working fluid, heat and mass transfer among the different phases, modifications in thermal and transport properties, and changes in chemical action and combustion. These processes occur commonly in the inlet, the compression turbomachinery, the bypass duct, and the flow mixer of the thrust nozzle assembly, and, probably, rather less frequently, in the prediffuser-combustor and the turbines; however, since a reduction in combustor exit temperature, and flameout may be due to either upstream effects in the turbomachinery, or local causes in the combustor, one must examine possible inter-phase heat transfer, local cooling and resulting changes in chemical reactions and reaction rates in various parts of the combustor. It is not possible, in general, to assure that all of the water, which may have entered the engine in various forms, would always be converted to the gas phase by the time the working fluid leaves the high pressure compressor, or even the combustor. Thus, both the state of the fluid and the cross-sectional distribution of water are of concern throughout the engine flowpath.

The presence of solid particles, ice, ice crystals, or hail, may be expected to produce much more severe effects in the "cold" sections of the engine, and rather less effects in the "hot" sections since water in liquid form requires considerably larger amounts of heat for phase transfer than ice does to melt into water.

The scaling of effects in various components, the engine, and the installation for different ingestion and operating conditions does not appear feasible in general. In a given case, and perhaps in a given class of engines, one may be able to set up scaling relations for selected effects.

for a specific inlet, or a stage of a compressor, the aerodynamic performance changes with various classes and amounts of the ingestion of a single substance such as water vapor or liquid water in droplet and film form are complicated but scaleable. Surprisingly, the scalability of effects in a combustor for similar ingestion are probably more easily discernible.

The next section provides the accomplishments in the project, followed by a list of publications in Section 3.

2. Accomplishments

2.1. Background

Prior to the initiation of the current research project, a number of studies had been undertaken at Purdue University in the subject of water ingestion:

i) Development of a model for spray generation by landing wheel motion over puddles of water on wet rough runways;

ii) development of a preliminary model for ingestion of landing wheel-generated spray into an engine inlet, e.g., on F-111 and B-1 aircraft;

iii) development of code WISGSK, a numerical procedure for prediction of the performance of an axial-flow compressor stage with water ingestion;

iv) development of a one-dimensional stage-stacking procedure for the use of WISGSK numerical procedure to multi-stage machines;

v) experimental studies on a 6-stage axial-flow compressor with a pressure ratio of 2.7 with air-water mixture; and

vi) development of probes for the measurement of pressure and temperature in an air-water mixture flow.

The outcome of this part of the research is published in Refs. 1-10.

2.2. Current Project Research

The principal interest in the researches under the current project has been in the following areas:

i) Development of analysis and a code named WINCOF for the determination of the performance of a fan-multistage compressor unit with water ingestion.

ii) Development of analysis and a code named WINCOF-I for the determination of the time-dependent performance of a fan-multistage compressor unit with water ingestion, that

accounts for the time-dependent processes from the inception of water ingestion, through the period of time over which all of the stages of the multi-stage compressor suffer ingestion, up to the instant of time when the last stage of the compressor is operating without water, either in the blade passage span or the blade-casing clearance.

iii) Demonstration of application of the codes, WINCOF and WINCOF-I to practical fan-compressor units.

iv) Determination of the transient performance of a turbofan engine with water ingestion, based on incorporating the WINCOF-I code and an ad hoc performance change estimation procedure for a combustor into a transient engine performance code.

v) Demonstration of application of the transient engine performance code with modifications as under (iv) to a practical turbofan engine.

vi) Conducting investigations on the effects of water ingestion into an axial-flow compressor, and, subsequently, into a turbofan engine under various operating and ingestion conditions.

vii) Development of analysis and a code named WINCLR for the determination of changes in blade-casing clearance for multi-stage axial flow compressor, taking into account the time-dependent nature of flow and clearance changes during water ingestion. And,

viii) demonstration of the application of the codes WINCLR and WINCOF-I interactively for the determination of blade-casing clearance changes in a practical multi-stage axial-flow compressor under different operating and ingestion conditions.

In all of the foregoing, water ingestion includes liquid water in droplet form of different sizes and film form of different thicknesses, and water vapor corresponding to various saturation levels in air. The air-water mixture is characterized by these parameters and the mass friction of different components of water.

The outcome of researches is published in Refs. 11-24.

2.3. Codes

The numerical codes WISGSK, WINCOF, WINCOF-I, and WINCLR are available from COSMIC. The codes include example problem input in each case. The address for COSMIC is COSMIC, 112 Barrow Hall, University of Georgia, 30601.

2.4. Illustrative Examples

The nature of the results obtained in a few illustrative cases may be found from the following illustrative examples.

2.4.1. Transient engine performance with water ingestion (Refs. 11-15).

Figure 1 presents the streamtubes considered in the fan-compressor unit of a generic turbofan engine with a core engine and a supercharger (booster) driven by a low pressure turbine. Figure 2 illustrates the booster performance with various amounts of water ingestion, generated using the WINCOF code.

Figure 3 illustrates the performance changes during a transient operation of the generic engine on a Standard Day during power demand changes from idle to maximum power, assuming that the water entering the combustor in unevaporated form becomes fully vaporized in the combustor.

2.4.2. Transient performance of a fan-compressor unit with water ingestion (Refs. 16-17).

A generic fan-compressor unit is considered with the booster and the core compressor operating at their design speeds and also under certain off-design conditions. Water is assumed to be ingested along with air into the inlet in the form of droplets and also as a film at the casing wall.

While the fan-compressor processes are recognized to be time-dependent, the performance is calculated assuming that a state of quasi-equilibrium is reached at the end of a certain period of time from the start of ingestion.

Figure 4 presents an assumed distribution of water fraction at the fan face. Considering a Standard Day operation, the resulting water distribution over the 14 stages of the high pressure compressor is shown in Fig. 5 under design operating conditions.

2.4.3. Transient performance of a generic fan engine with water ingestion (Refs. 18-20).

A generic turbofan engine is considered as shown in Fig. 6.

The performance of the high pressure compressor is shown in Fig. 7 for the case in which under design operating conditions the mass fraction of water is instantly changed form 2.0 to 8.0 per cent.

Considering the engine as a whole; and a specific flight operation, the performance of the engine is shown in Fig. 8 for the following case.

- $x_W = 0.4$
- flight from 1 to 3 in the altitude Mach number figure.

- operation:

time (s)	0	10	30	40	90	120
PLA (deg)	57	97.01	97.01 →	57	57	57
Altitude (kft)	15	15	15	→	8	8
Mach	0.6	0.6	0.6	→	0.3	0.3

2.4.4. Estimation of casing clearance changes during water ingestion (Refs. 17, and 20-23)

Considering a generic compressor ingesting water, and assuming time-dependent performance changes in the compressor, the WINCLR code has been utilized to establish the changes in casing clearance. The nature of changes is illustrated in Fig. 9.

Under the assumption of time-dependent operation of a compressor during water ingestion as in the foregoing, it is necessary to utilize the WINCOF-I and the WINCLR codes interactively, as shown in Fig. 10.

3. Discussion

The research undertaken under the project, along with the background that existed at the time of initiation of the project, and the outcome of researches in two related projects (Ref. 25-38), has provided a basis for estimating the effects of water vapor and water ingestion into (a) an inlet, (b) an axial-flow compressor, (c) a fan-axial compressor unit, and (d) a prediffuser-combustor unit. In addition, a methodology has been established for incorporating component performance changes into an engine transient performance code, and thereby providing a means of establishing the time-dependent performance changes in jet and turbofan engines under different operating and ingestion conditions. Finally, a means of determining blade-casing clearance changes during water ingestion has been developed, that takes into account the transient performance of turbomachinery during such ingestion.

From probing the effects of water ingestion in liquid and vapor form into axial-flow compressors (through experiments and predictions) and turbofan engines (through predictions), the following observations can be made:

i) The effects of both water vapor and water ingestion depend on their mass fraction in the air-water mixture. However, in the case of liquid water, both the form and the size (diameter and its distribution for droplets, and thickness for films) have substantial influence, except when the amount of water is very small (less than 0.5%) or quite large (over 8%).

ii) Whether water is ingested in vapor or drop form, it can be expected that a film probably becomes formed over some part of the inlet surface. In the case of water droplet ingestion, one can expect a specific, generally nonuniform distribution to evolve at the engine (or the fan) face whatever the distribution in the air capture streamtube. One must also take into account the "scooping" effect that leads to the entry of a larger amount of water than in the

capture streamtube into the inlet. The inlet geometry, including the spinner, and the engine operating condition, thus, determine the distribution of water at the engine face.

iii) The action of the spinner in combination with that of the fan can lead to a substantial diversion of water entities into the bypass stream in a turbofan engine. Along with the modifications in the fan, one can expect a new distribution of water at entry to the low pressure compressor.

iv) Whether or not there is a film to start with ahead of a fan or a compressor, a film comes into existence in the blade-casing clearance, if only due to the centrifugal action in the flowfield and the containment of the casing.

The film, formed in the clearance space, moves at a lower speed than the adjoining air-water mixture in the span of the blade row. It can, in general, be discontinuous in thickness along a multi-stage unit. Some film can be expected to be present at the exit of a high pressure compressor in all cases.

Such a film can affect sensors at the engine casing. If the sensors are part of the control system actuators, erroneous actions follow, and the performance of the compressor and thus of the engine can change substantially.

v) The aerodynamic performance of a fan and a compressor deteriorate with water ingestion. Any gain from the cooling of the gas phase during interphase heat transfer reduces when the amount of water increases. The processes here must be distinguished from those occurring when a spray of water is injected by design or a precooler is utilized with no mixing of the fluids.

Ingestion can cause stalling and surging of a fan and compressors.

vi) The most dominant process in a combustor when water is present with air is the interphase heat transfer and the resulting temperature reduction. As a consequence of such a temperature change, both chemical reactions and their rate become affected, and may cause first order changes in engine performance.

The introduction of water in any form in an unregulated fashion into a combustor can lead to arbitrary amounts of unburnt hydrocarbons and pollutants.

vii) An engine suffering water ingestion probably does not attain a steady state even if the ingestion is steady and persists for a long time (larger than about 60s).

viii) The flight descent idle operating condition is in most respects the most affected by water ingestion. In other operating conditions, there is a loss of power, but probably not severe except when the amount of ingestion increases above 8%.

Under the flight descent idle operating condition, the ingestion of 2 to 4% of water can give rise to an inability for the low pressure turbine to power successfully the fan-low pressure compressor unit attached to it, even if the fuel supply is increased.

ix) The extent of performance changes in different engines is different, and it is generally not feasible to provide scaling loss for the effects based on ingestion and operating conditions. However, the nature of such changes can be estimated within a class of engines.

x) In undertaking on-ground testing simulating conditions likely to be of significance in flight, it is necessary to establish (1) the distribution of the state and amount of water at several locations along the engine between the inlet highlight and the exit of the high pressure compressor, and (2) the changes in performance of the engine under a selected number of operating conditions.

It must be noted that the preceding statements take no account of the presence and effects of bypass doors, vents, and valves. This is a set of devices for which there are no reliable data for air-water mixture operation, and thus, no guidance in design or installation. They can introduce major changes in the amount and distribution of the discrete phases of water along the flowpath in compressors.

Finally, there is a need for at least one set of definitive tests on selected components and engines.

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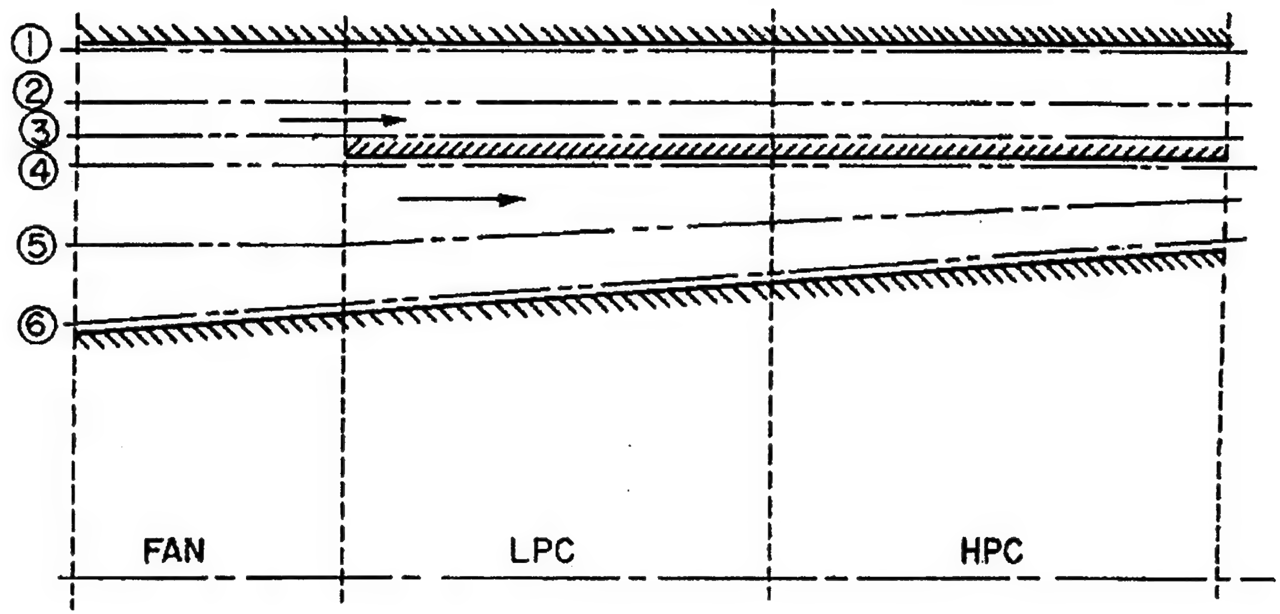
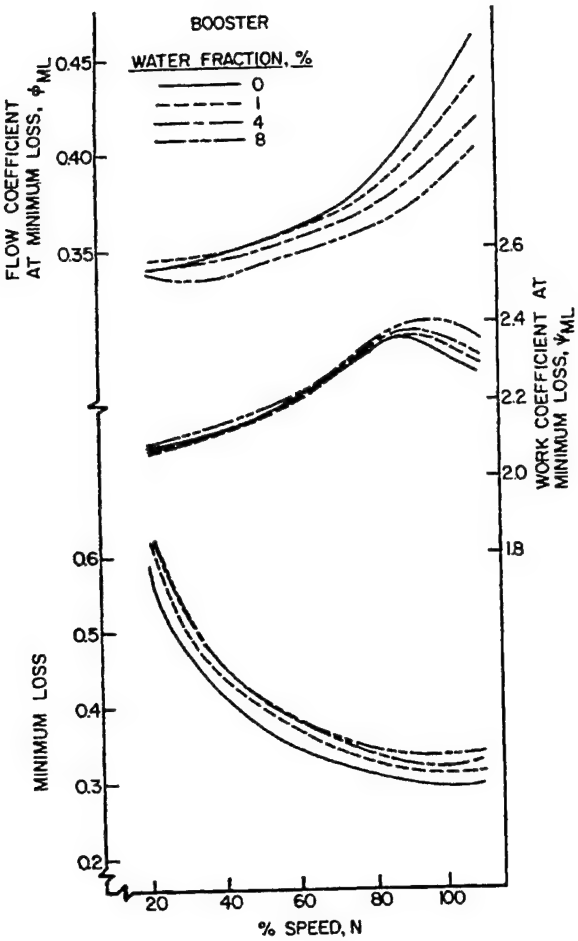
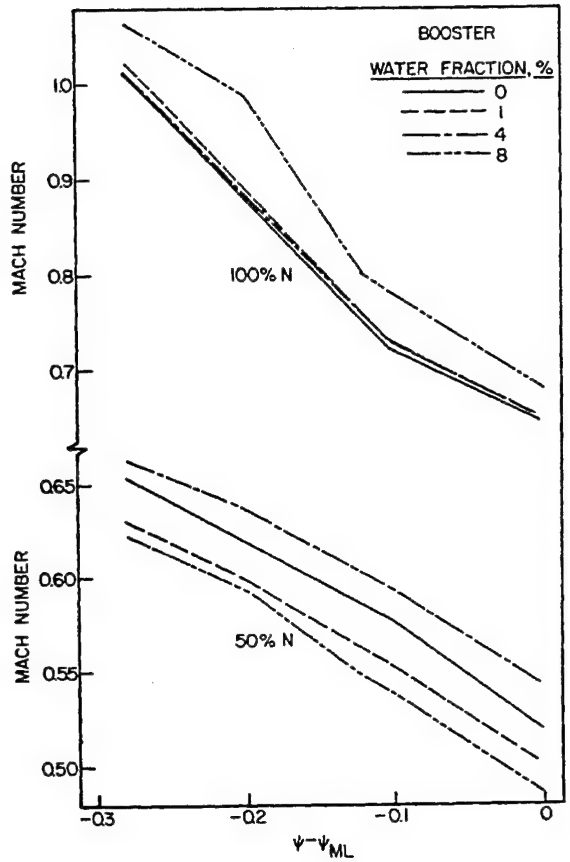


Figure 1. Identification of Streamtubes in the Fan-Compressor Unit.





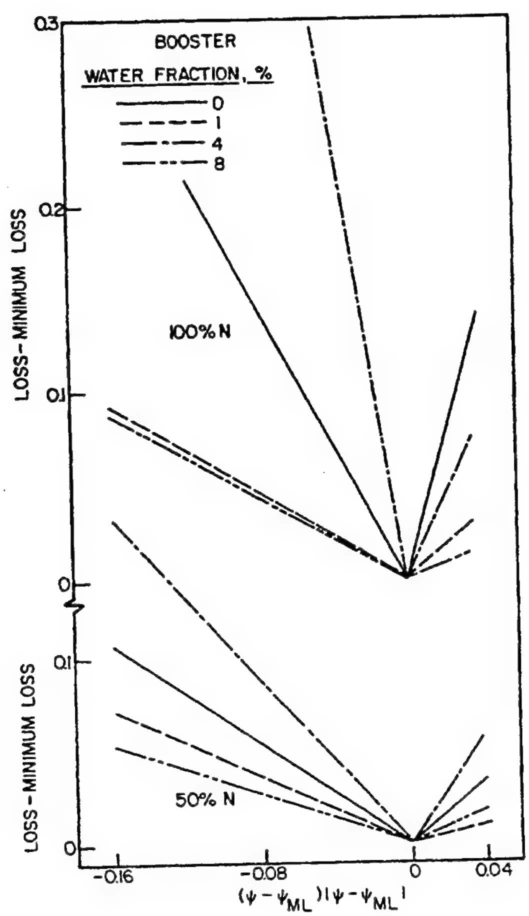


Figure 2. Booster Performance in the Form of Booster Backbone Curves.

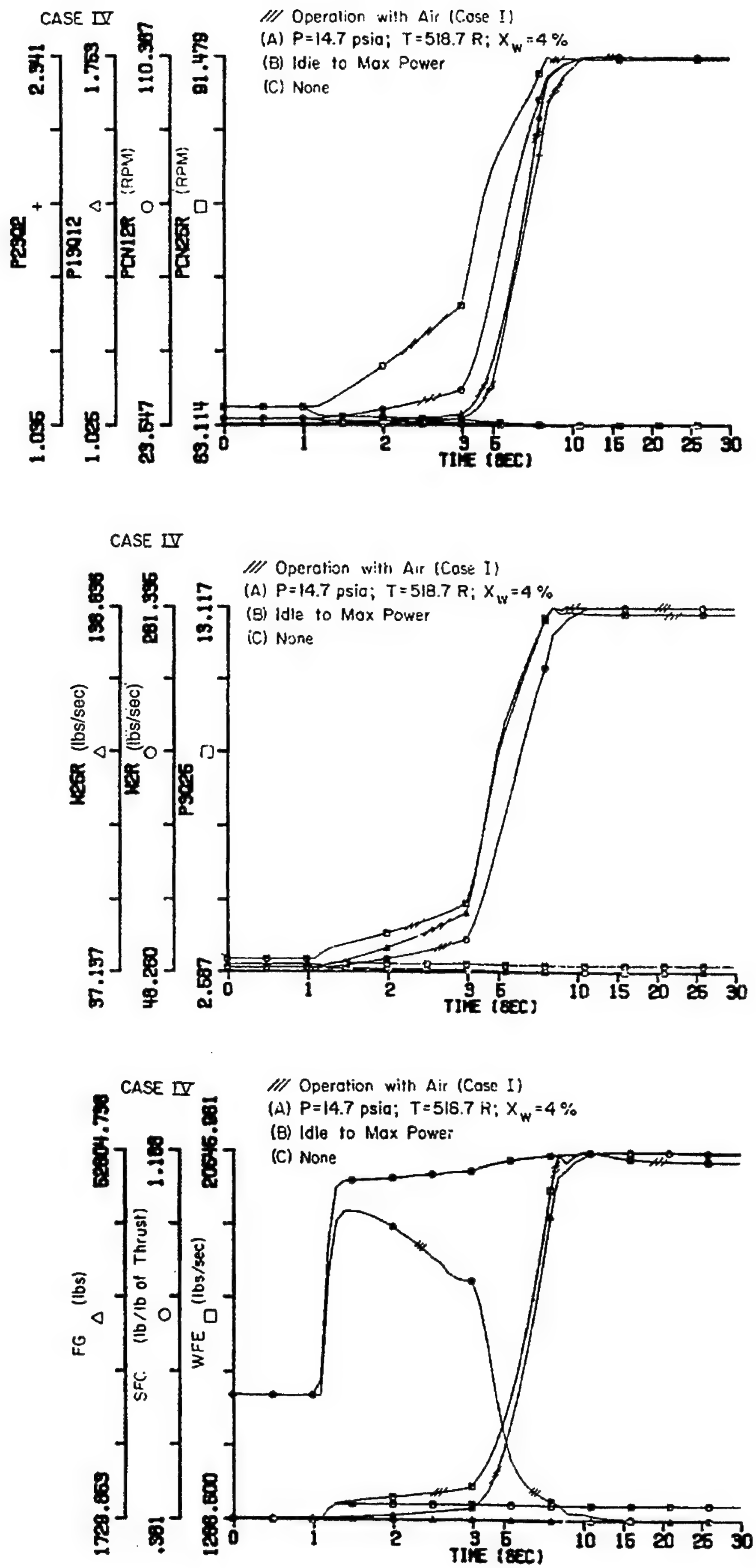


Figure 3. Performance of a Generic Engine Under a Quasi-Steady Approximation.

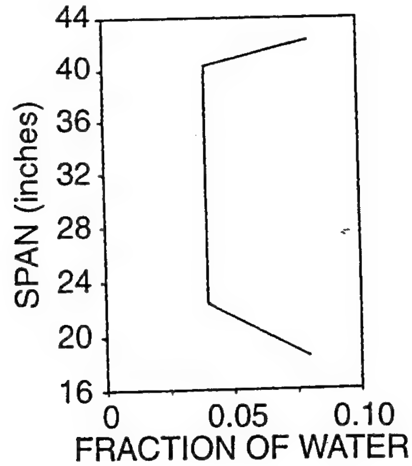
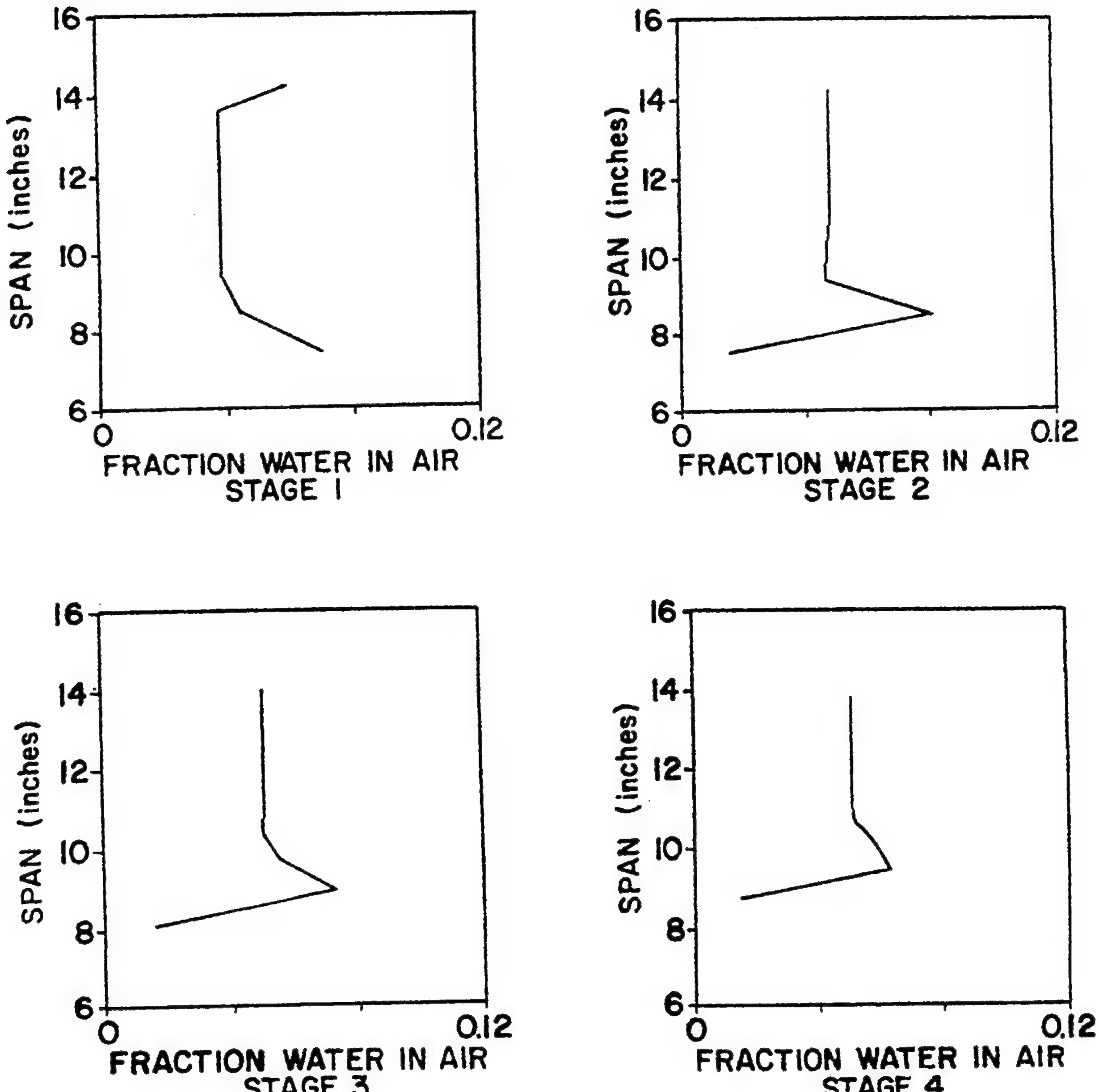
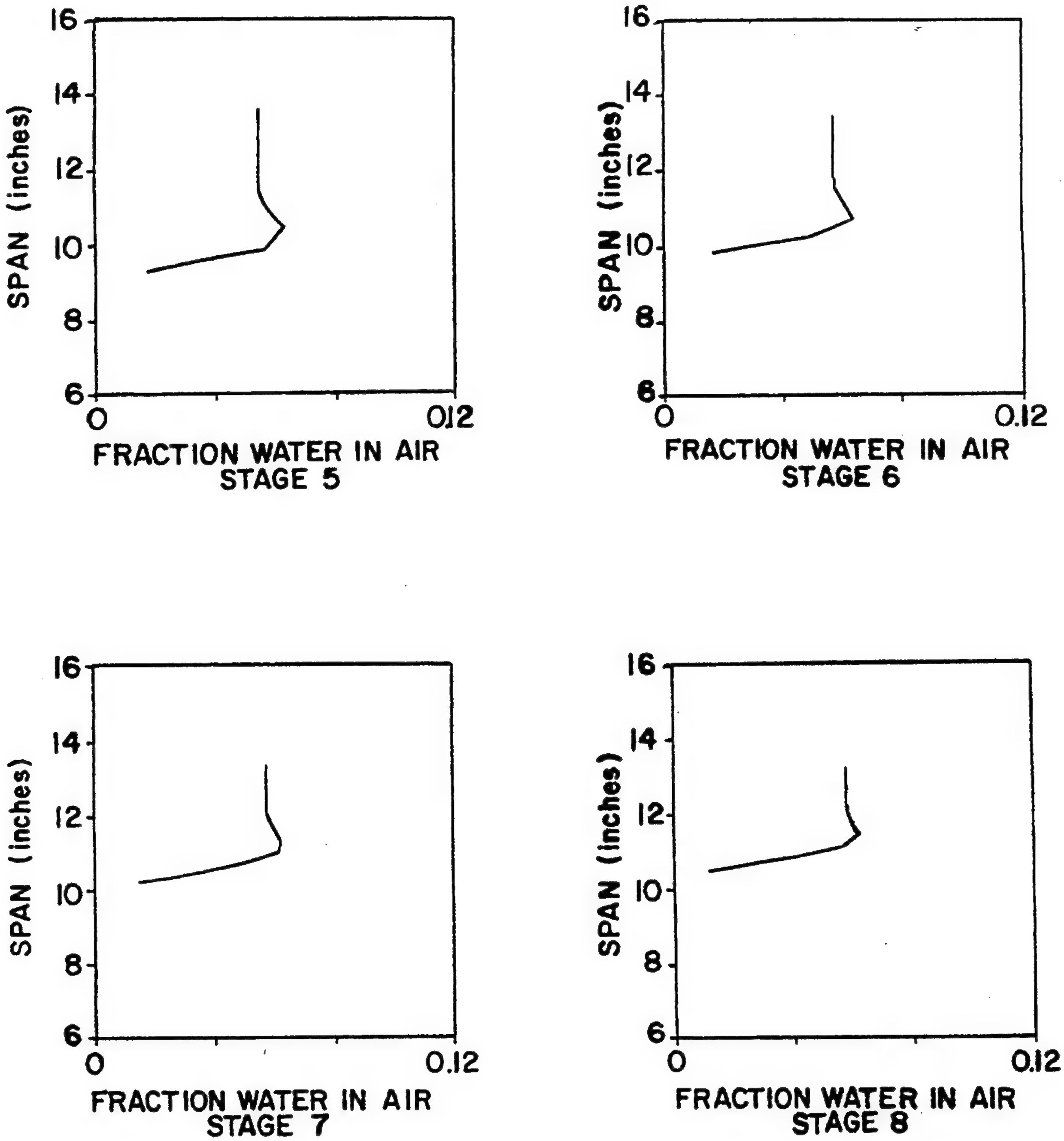


Figure 4. Assumed Distribution of Water Mass Fraction at Entry to the Fan of a Generic Fan-Compressor Unit.



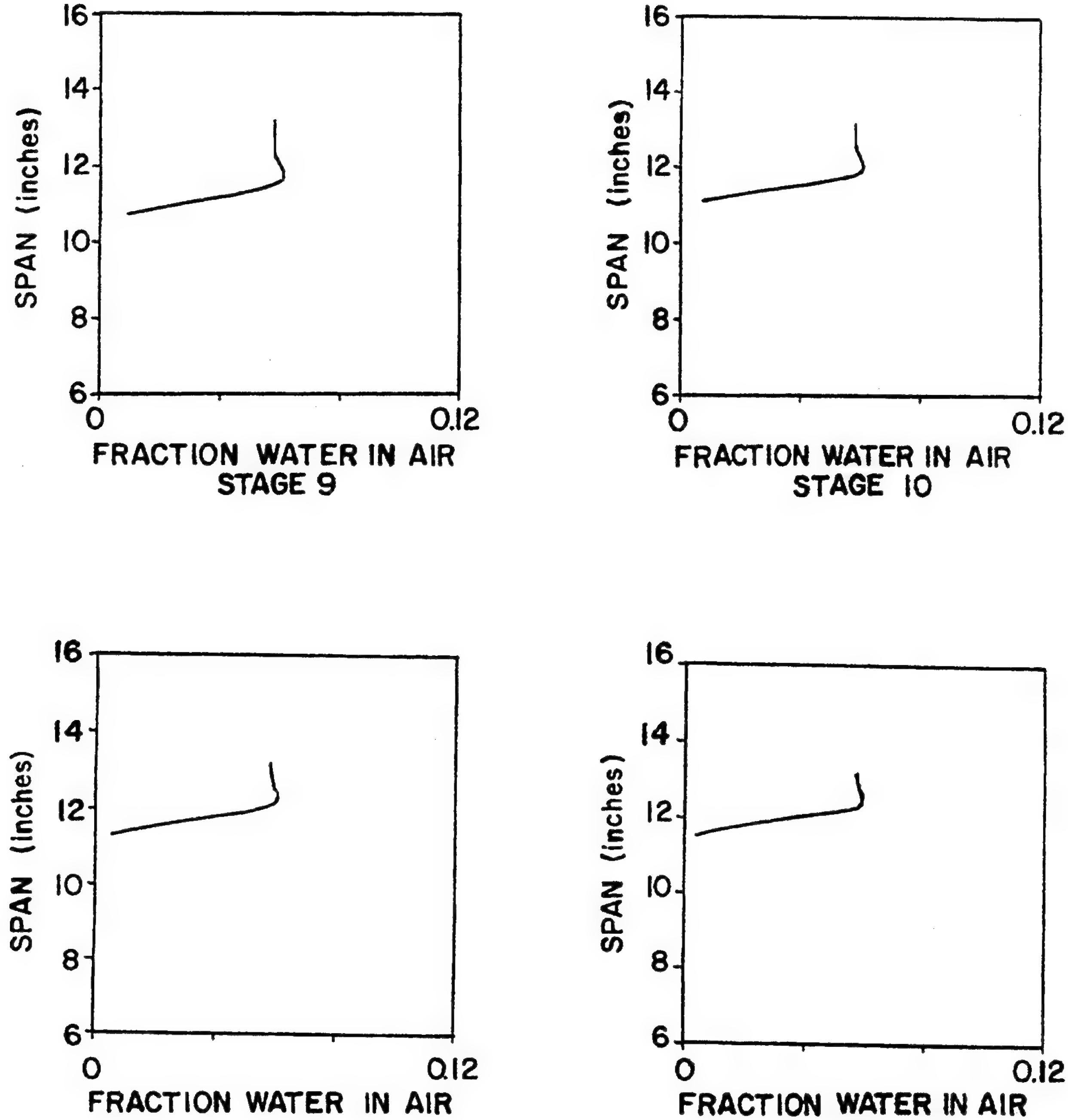
(a)

Figure 5. Water (a, b, c, d) and Water-Vapor (e, f, g, h) Distributions in the Various Stages of the Generic High Pressure for the Entry Conditions Given in Fig. 4.



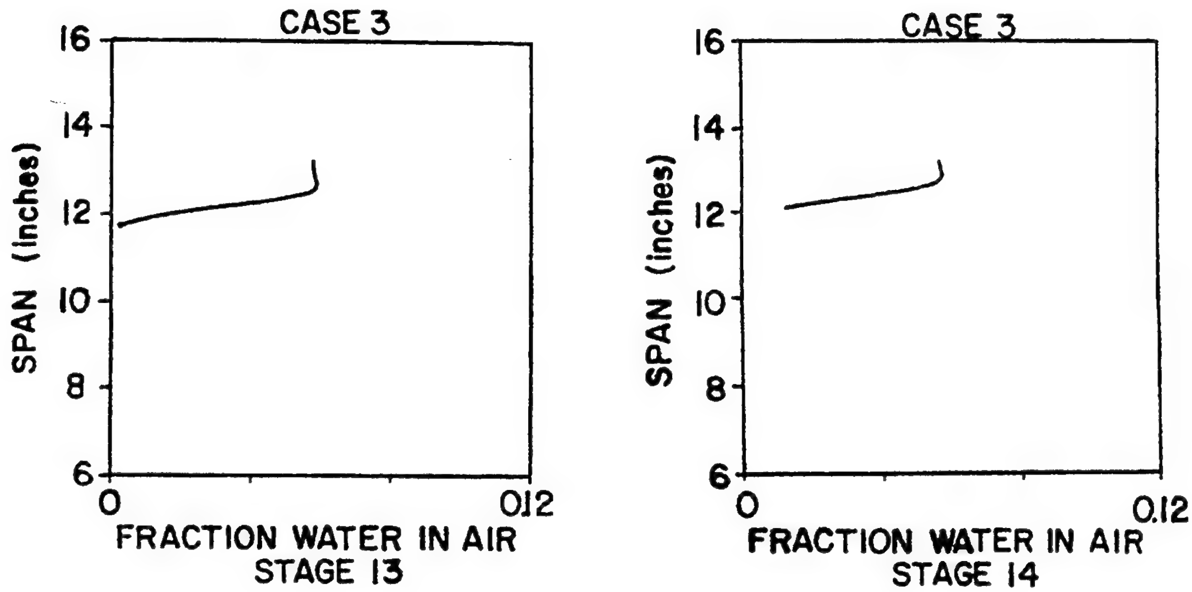
(b)

Figure 5. Water (a, b, c, d) and Water-Vapor (e, f, g, h) Distributions in the Various Stages of the Generic High Pressure for the Entry Conditions Given in Fig. 4. (Continued)



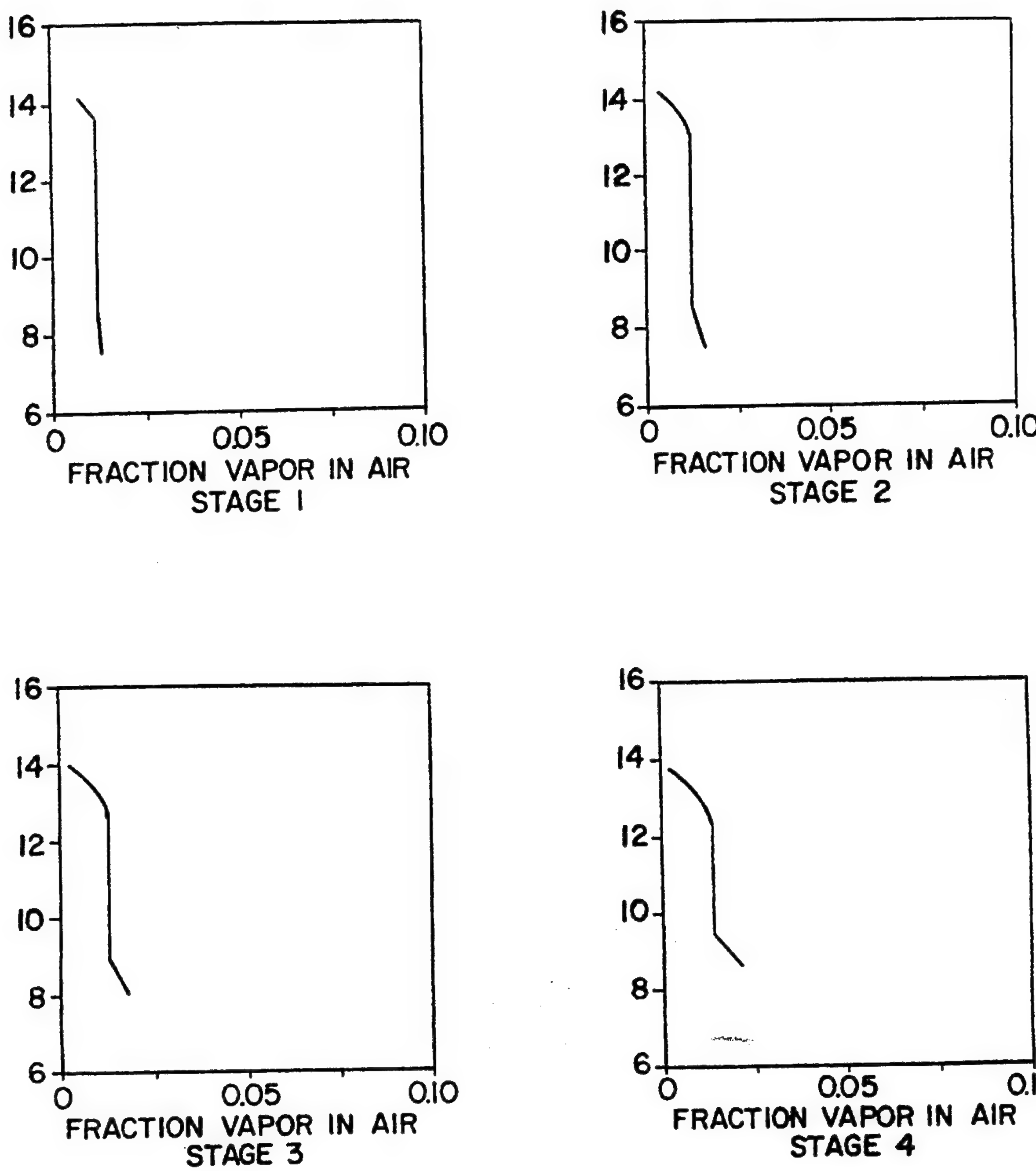
(c)

Figure 5. Water (a, b, c, d) and Water-Vapor (e, f, g, h) Distributions in the Various Stages of the Generic High Pressure for the Entry Conditions Given in Fig. 4. (Continued)



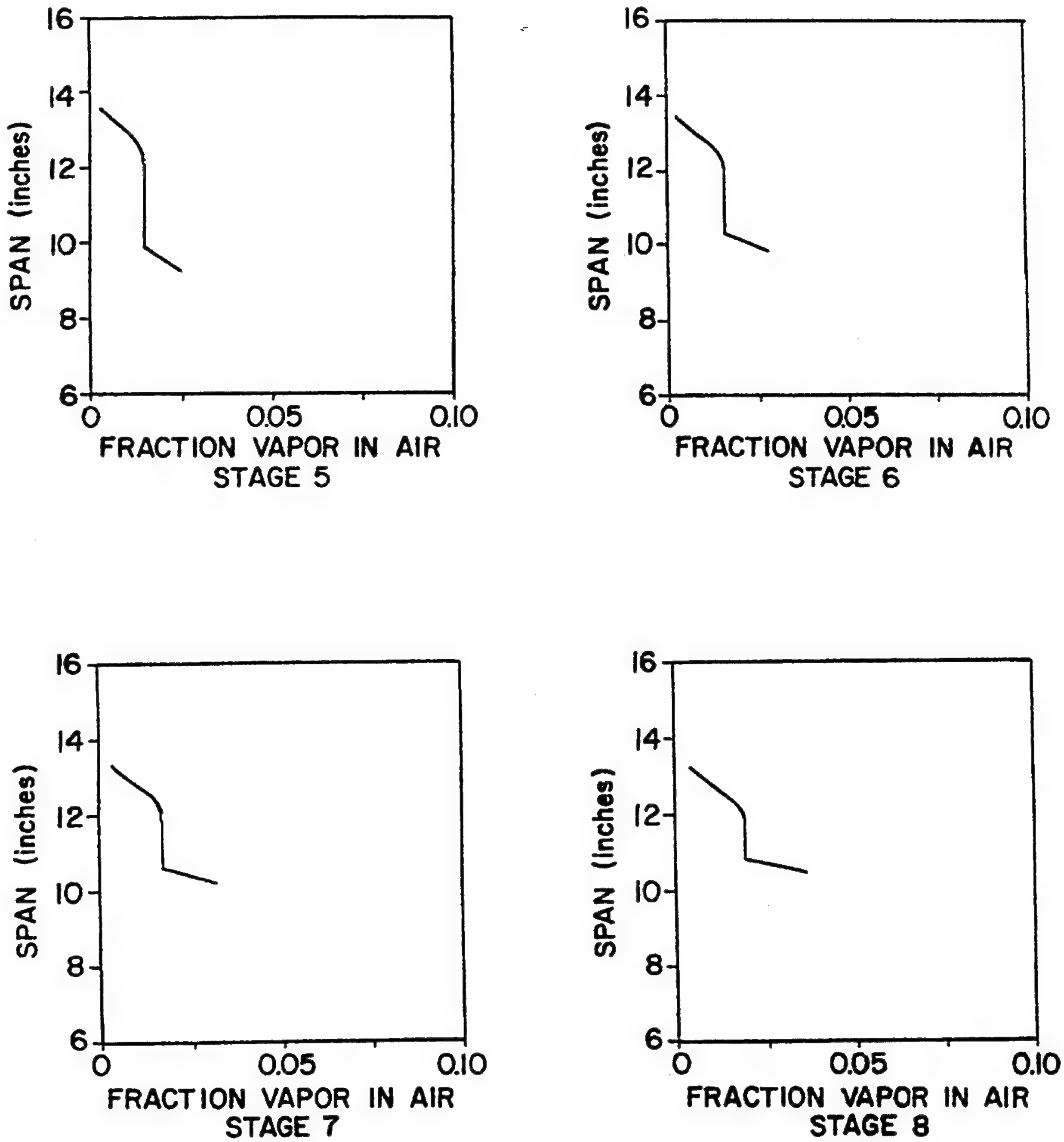
(d)

Figure 5. Water (a, b, c, d) and Water-Vapor (e, f, g, h) Distributions in the Various Stages of the Generic High Pressure for the Entry Conditions Given in Fig. 4. (Continued)



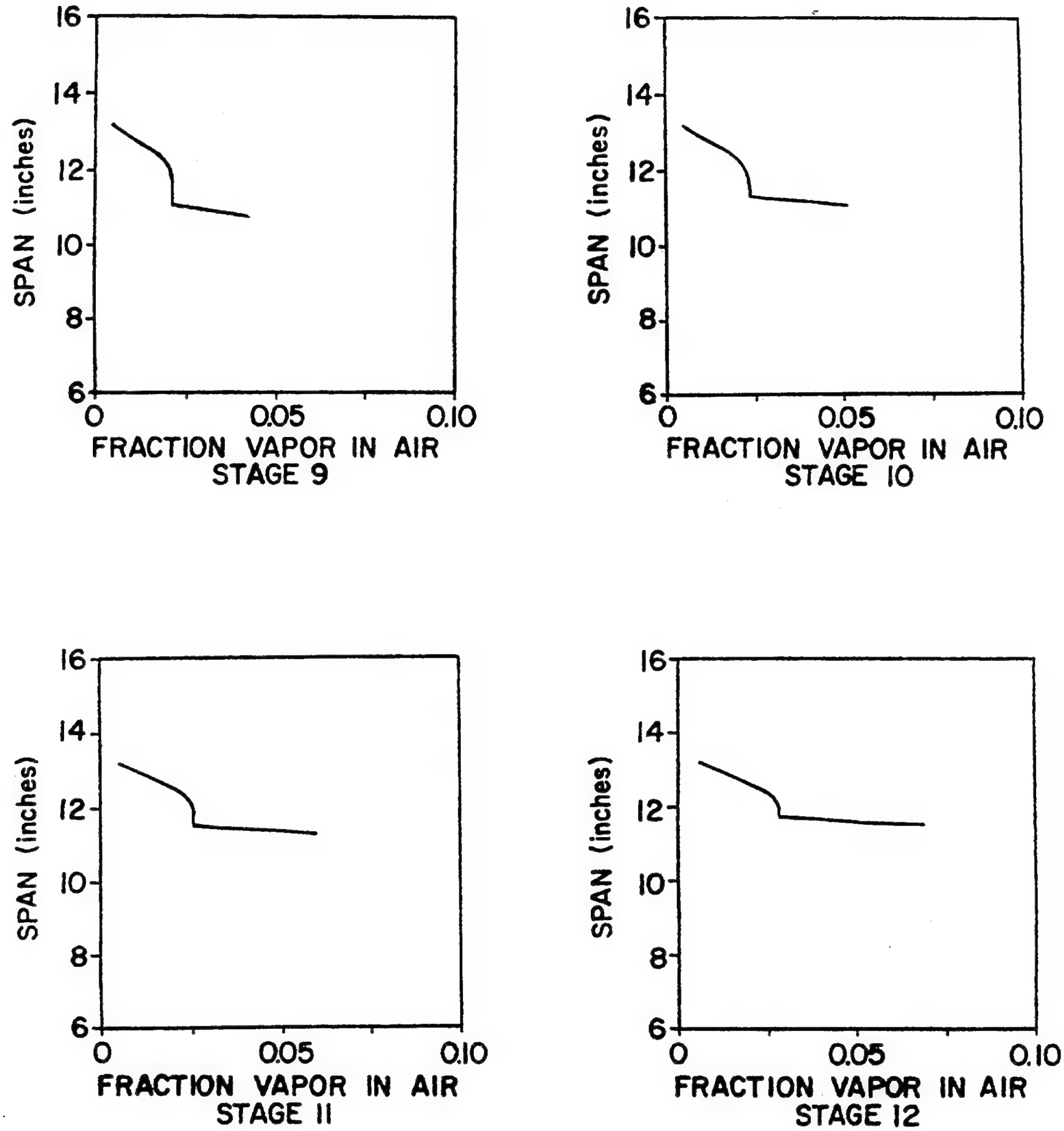
(e)

Figure 5. Water (a, b, c, d) and Water-Vapor (e, f, g, h) Distributions in the Various Stages of the Generic High Pressure for the Entry Conditions Given in Fig. 4. (Continued)



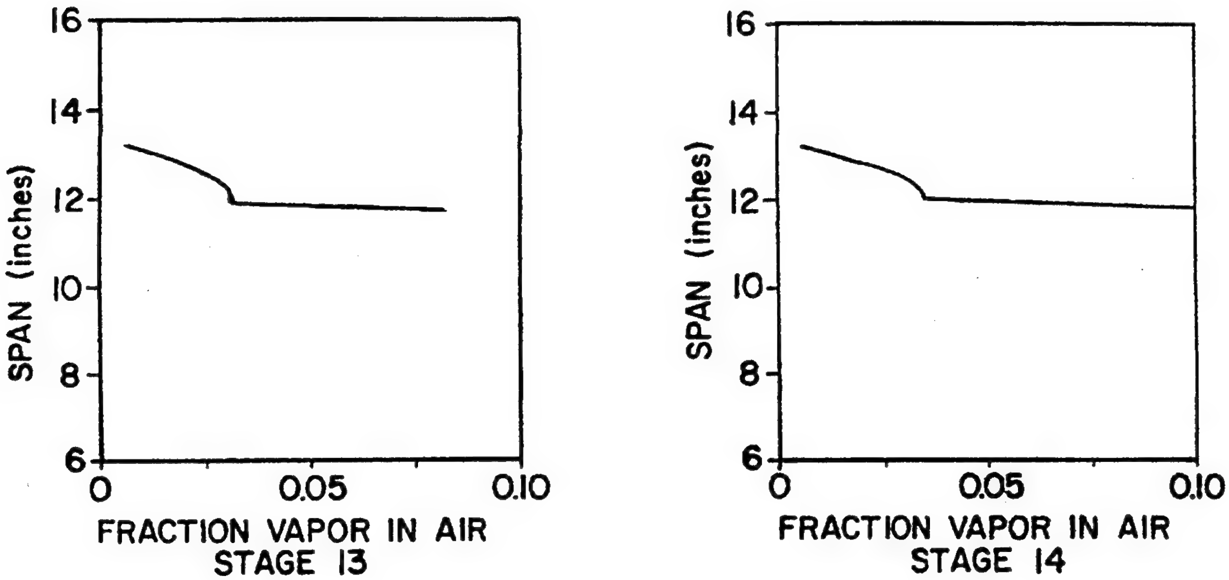
(f)

Figure 5. Water (a, b, c, d) and Water-Vapor (e, f, g, h) Distributions in the Various Stages of the Generic High Pressure for the Entry Conditions Given in Fig. 4. (Continued)



(g)

Figure 5. Water (a, b, c, d) and Water-Vapor (e, f, g, h) Distributions in the Various Stages of the Generic High Pressure for the Entry Conditions Given in Fig. 4. (Continued)



(h)

Figure 5. Water (a, b, c, d) and Water-Vapor (e, f, g, h) Distributions in the Various Stages of the Generic High Pressure for the Entry Conditions Given in Fig. 4. (Concluded)

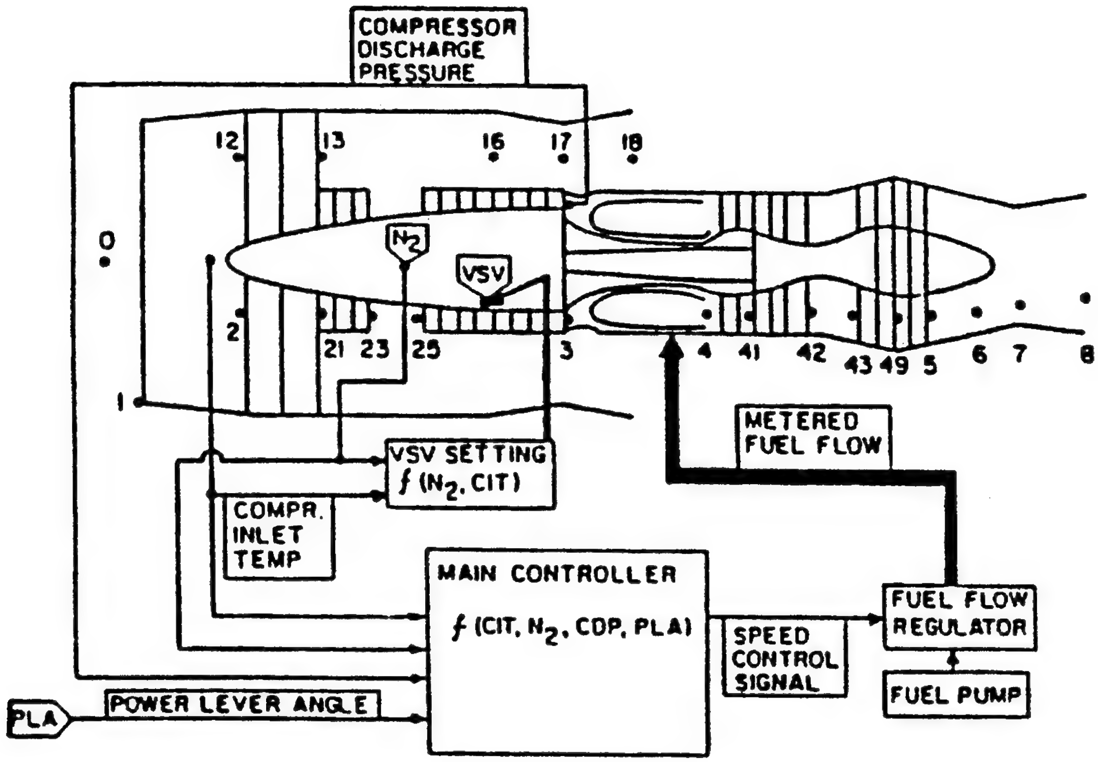


Figure 6. A Generic Turbofan Engine.

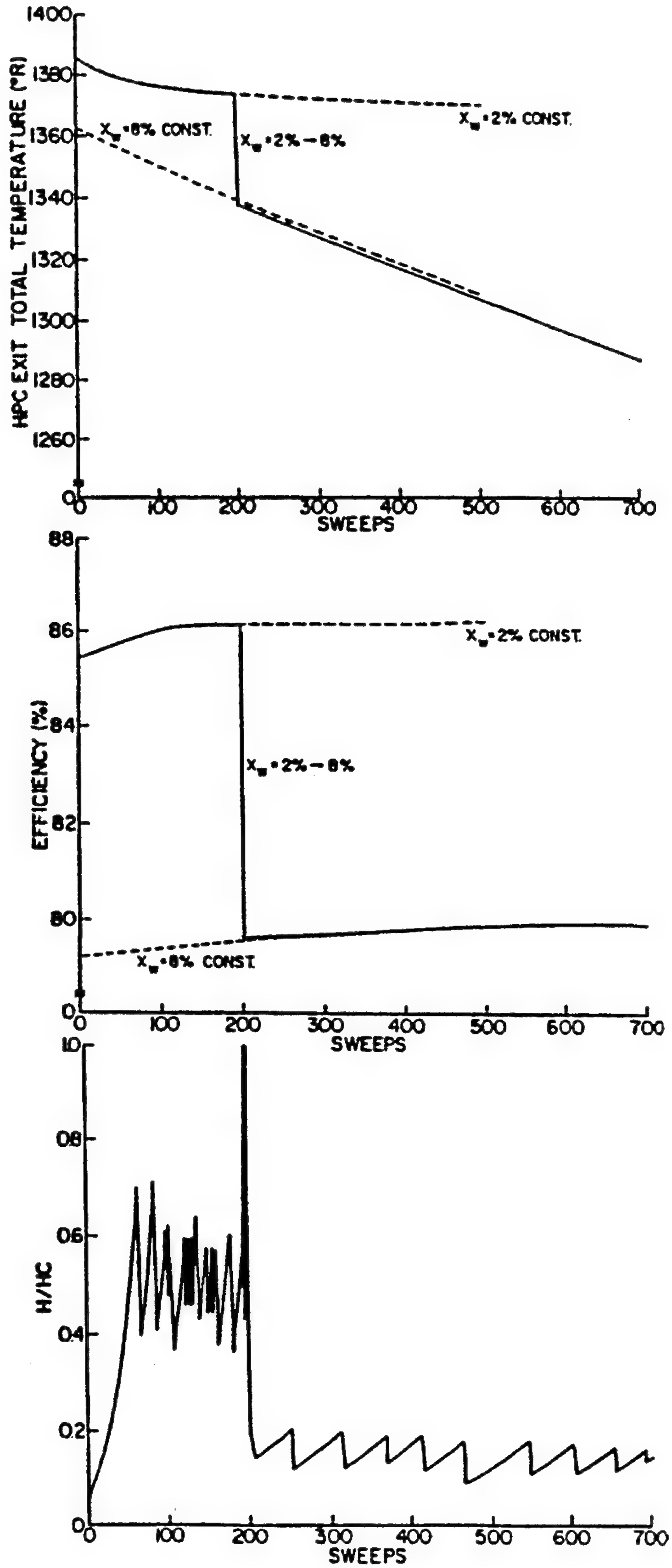


Figure 7. Performance of the High Pressure Compressor of the Generic Turbofan Engine shown in Figure 6: Design Speed; Flow Coefficient = 0.45.

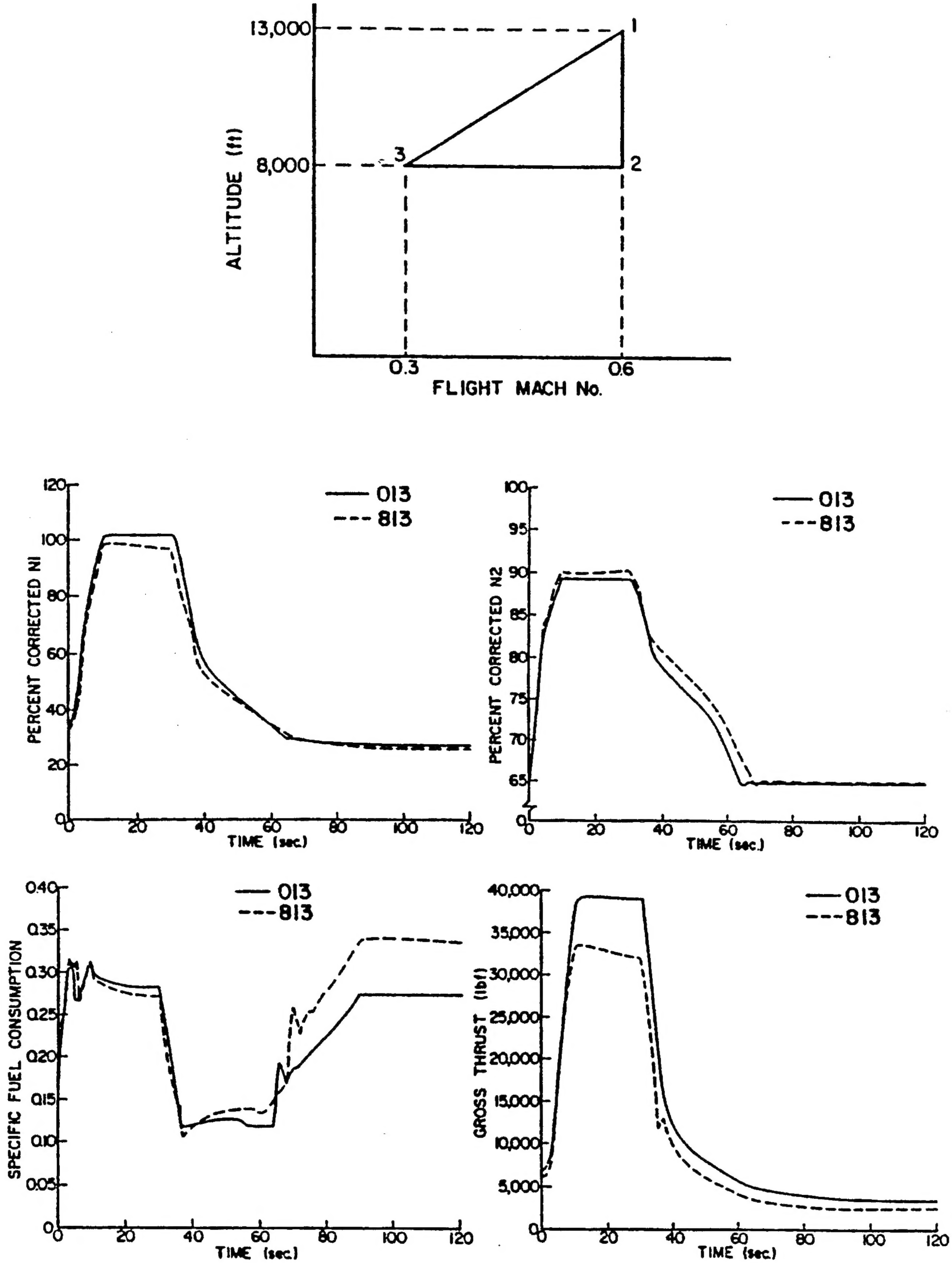


Figure 8. A Specific Flight-Operation and the Performance of the Engine.

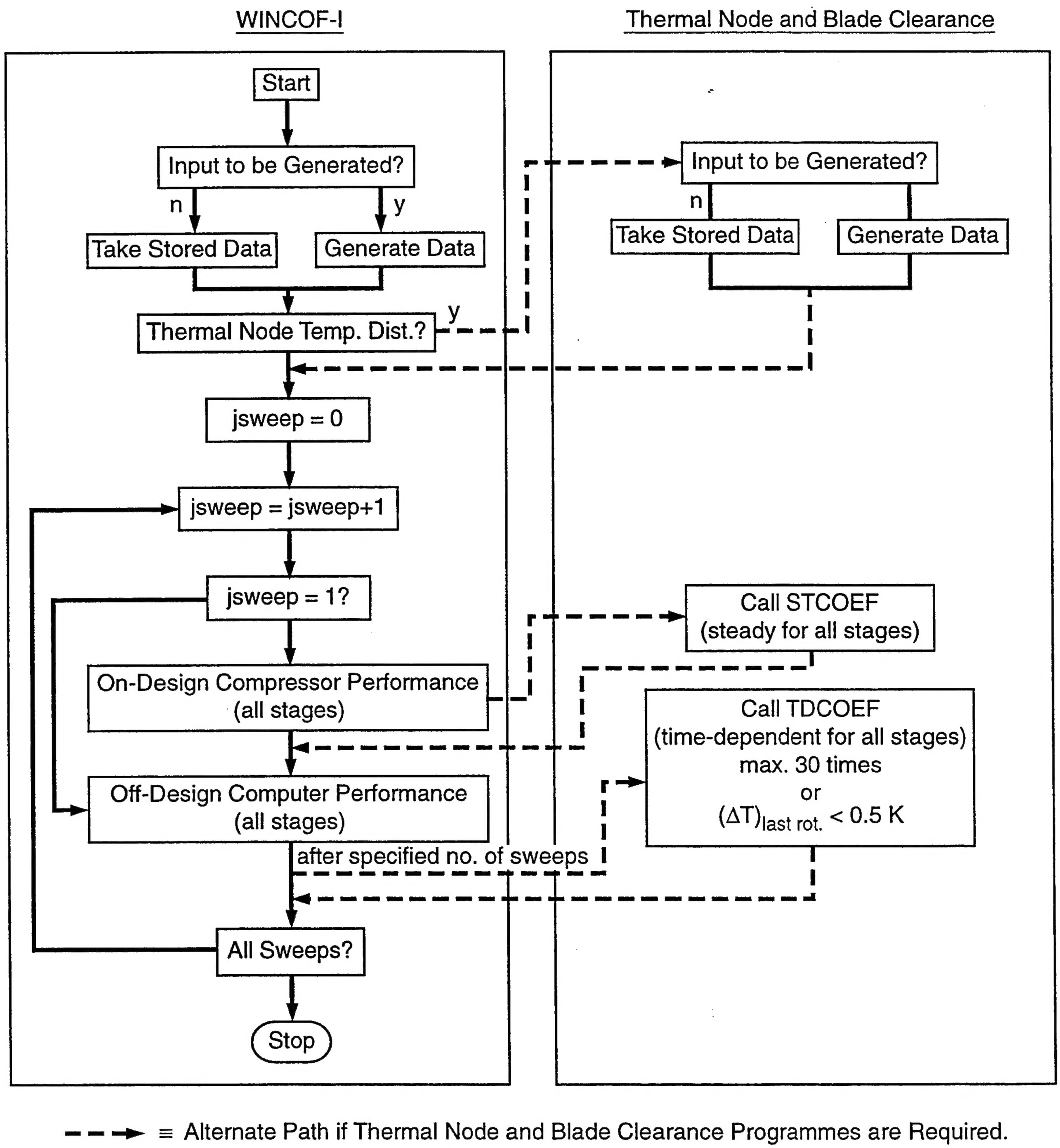


Figure 9. Determination of Casing Clearance Changes.

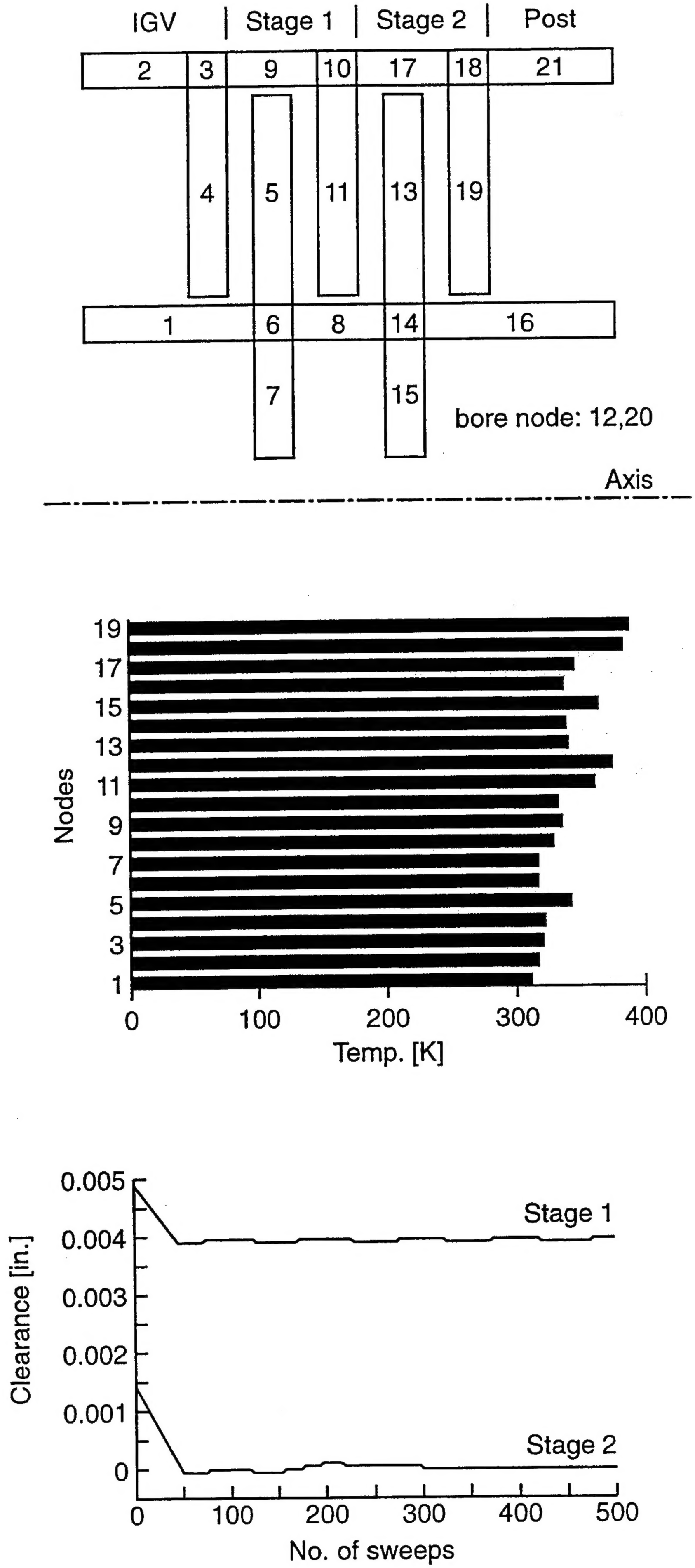


Figure 10. Interactive Use of WINCOF-I and WINCLR Codes.

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13. ABSTRACT ***(Maximum 200 words)***

The research on dynamic performance of high bypass turbofan engines includes studies on inlets, turbomachinery and the total engine system operating with air-water mixture; the water may be in vapor, droplet, or film form, and their combinations. Prediction codes (WISGS, WINCOF, WINCOF-1, WINCLR, and Transient Engine Performance Code) for performance changes, as well as changes in blade-casing clearance, have been established and demonstrated in application to actual, generic engines. In view of the continuous changes in water distribution in turbomachinery, the performance of both components and the total engine system must be determined in a time-dependent mode; hence, the determination of clearance changes also requires a time-dependent approach. In general, the performance and clearances changes cannot be scaled either with respect to operating or ingestion conditions. Removal of water prior to phase change is the most effective means of avoiding ingestion effects. Sufficient background has been established to perform definitive, full scale tests on a set of components and a complete engine to establish engine control and operability with various air-water vapor-water mixtures.

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